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Space Environmental Effects on the Optical Properties of Selected Transparent Polymers

David L. Edwards

Physical Sciences and Environmental
Effects Branch, NASA, MSFC, AL 35812
Phone: 205-544-4081/Fax: 205-544-5103
E-mail: david.edwards@msfc.nasa.gov

Whitney C. Hubbs

Physical Sciences and Environmental
Effects Branch, NASA, MSFC, AL 35812
Phone: 205-544-8375/Fax: 205-544-5103
E-mail: whitney.hubbs@msfc.nasa.gov

Douglas J. Willowby

Electrical Power Branch, NASA, MSFC, AL 35812
Phone: 205-544-3334/Fax: 205-544-5841
E-mail: douglas.willowby@msfc.nasa.gov

Michael F. Piszczor, Jr.

Photovoltaic and Space Environments Branch
NASA, LeRC, Cleveland, OH 44135
Phone: 216-433-2237/Fax: 216-433-6106
E-mail: michael.piszczor@lerc.nasa.gov

Dr. Mary L. Bowden

AEC Able Engineering, Inc., Goleta, CA 93116-0588
Phone: 301-405-0011/Fax: 301-314-9001
(University of Maryland)

ABSTRACT

Transparent polymer films are currently considered for use as solar concentrating lenses for spacecraft power and propulsion systems. These polymer films concentrate solar energy onto energy conversion devices such as solar cells and thermal energy systems. Conversion efficiency is directly related to the polymer transmission. Space environmental effects will decrease the transmission and thus reduce the conversion efficiency. This investigation focuses on the effects of ultraviolet and charged particle radiation on the transmission of selected transparent polymers. Multiple candidate polymer samples were exposed to near ultraviolet (NUV) radiation to screen the materials and select optimum materials for further study. All materials experienced transmission degradation of varying degree. A method was developed to normalize the transmission loss and thus rank the materials according to their tolerance of NUV. Teflon™ FEP and Teflon™ PFA were selected for further study. These materials were subjected to a combined charged particle dose equivalent to 5 years in a typical geosynchronous Earth orbit (GEO). Results from these NUV screening tests and the 5 year GEO equivalent dose are presented.

INTRODUCTION

Recently, much emphasis has been placed on the concentration of solar energy for spacecraft propulsion and electrical power systems. Increasing interest in lightweight structures that possess small stowage space and deploy on orbit are driving development towards flexible solar concentrators.

The testing reported in this paper was a joint effort between the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC) and Lewis Research Center (LeRC), and AEC Able Engineering Co., Inc., to evaluate candidate materials for the Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET) program. SCARLET is a joint Ballistic Missile Defense Organization (BMDO) and NASA program to develop and demonstrate advanced photovoltaic concentrator array technology that is applicable to a variety of government and commercial space missions (Jones and Murphy, 1996). Under this program, AEC Able will fabricate a 2.6 kW concentrator solar array as the primary power source for NASA's New Millennium Program Deep Space One (DS-1) spacecraft (Casani).

A variety of transparent polymers were initially studied for use as the material of choice for the arched linear Fresnel lens optics. However, schedule demands and the lack of extensive environmental test data precluded the use of these materials for the DS-1 mission. Still, these materials offer a number of significant advantages for the further implementation of this technology and will continue to be studied.

The Physical Sciences and Environmental Effects Branch was selected to characterize the candidate transparent polymers provided by AEC Able. The testing conducted under this effort did not include any effect of solar concentration due to Fresnel optics, but examined the total transmission degradation of the polymer. The ultimate goal was to determine an optimum transparent polymer from a large selection of commercially available candidate materials. Transmission was determined to be the characterizing property for optimum material

selection since loss of transmission of the polymer lens leads to a drop in solar cell power output. Clearly, maintaining high optical transmission throughout the life of the mission is essential to the performance of the solar cells.

This investigation centers on the transmission evaluation of commercially available polymers when exposed to a simulated space environment. In order to compare the various candidates, a technique was developed that normalized the transmission degradation and thus allowed the polymers to be ranked according to transmission tolerance to space environmental effects.

EXPERIMENTAL PROCEDURE

Description of the Facility

The MSFC Physical Sciences and Environmental Effects Branch investigates the effects of the space environment on materials. This branch operates several high vacuum NUV and vacuum ultraviolet (VUV) exposure systems, atomic oxygen (AO) exposure systems, and a unique combined environmental effects (CEE) test system. The CEE system offers the capability to irradiate samples to a simultaneous or sequential exposure to protons, low-energy electrons, high-energy electrons, NUV, and VUV (Edwards et al., 1996). The CEE system also allows in-vacuum reflectance measurements of the temperature controlled samples.

These test systems are verified to be contamination-free prior to any testing by exposing an optical witness sample (OWS) to NUV for 1 week in vacuum. The NUV is included because it enhances contaminant photodeposition (e.g., photofixing). The OWS of greatest sensitivity to contamination photodeposition is an MgF_2/Al mirror. This

OWS mirror is characterized, pretest, using a VUV reflectance system. The mirror is then exposed to NUV as described above and analyzed, posttest, using the same VUV reflectance system. The criterion to pass the contamination-free verification test is less than $\pm 3\%$ $\Delta R/R$ for all wavelengths in the range from 121 to 200 nanometers (nm).

Screening Test

Eleven transparent polymers (see Table 1) were selected by AEC for the first screening test. This screening test consisted of simultaneously exposing all samples to an equivalent dose of NUV and then selecting the most NUV-tolerant materials for further testing.

Pre-exposure transmission spectra were obtained on these 11 samples using a Lambda 19 spectrometer analysis system. Transmission spectra were obtained over the wavelength range from 185 to 2200 nm. The analytical normalization techniques, discussed in the Analytical section, were applied over the wavelength range from 300 to 1000 nm, because this range encompasses the operating range of several types of solar cells.

The samples were placed in the vacuum test system and the NUV exposure was initiated when the vacuum level reached 5×10^{-6} torr. Based on pretesting characterization, the NUV intensity was determined to be, on average, 2.75 NUV Suns. This intensity was determined by integrating the NUV source output over the wavelength range from 250 to 400 nm and comparing the results to the accepted values for a solar constant at air mass zero (AM0) (ASTM E 490-73a, 1992). The samples were continuously exposed to NUV for 474.5 hours and with the NUV intensity at 2.75 NUV Suns, which yields an exposure duration of approximately 1300 equivalent Sun hours (ESH). Figure 1 shows the transmission spectra of one of the 11 samples exposed to 1300 equivalent Sun hours of NUV.

TABLE 1. Eleven transparent polymers selected for the first screening test, an exposure to 1300 ESH NUV. Solar transmissivity values are shown for control and exposed polymers.

Material	Control Transmissivity (Tc) %	Exposed Transmissivity (Te) %	Transmission Degradation (Td) %
Lexan (7 mils)	77.92	56.41	21.51
Triton COR (2 mils)	85.30	59.43	25.87
UVR T2 Tefzel (2.5 mils)	84.33	77.55	6.78
Acrylic (10 mils)	89.28	65.34	23.94
LaRC CP1 (1 mil)	74.12	64.64	9.48
Tefzel 500 LZ (5 mils)	90.60	74.60	16.00
T2 Teflon™ PFA (4 mils)	94.66	83.71	10.95
T2 Tefzel 500 ZM (5 mils)	90.38	78.35	12.03
Teflon™ PFA (3 mils)	94.31	76.09	18.22
UVR T2 Tefzel (5 mils)	82.25	74.84	7.41
UVR Coated PET (7 mils)	78.57	55.52	23.05

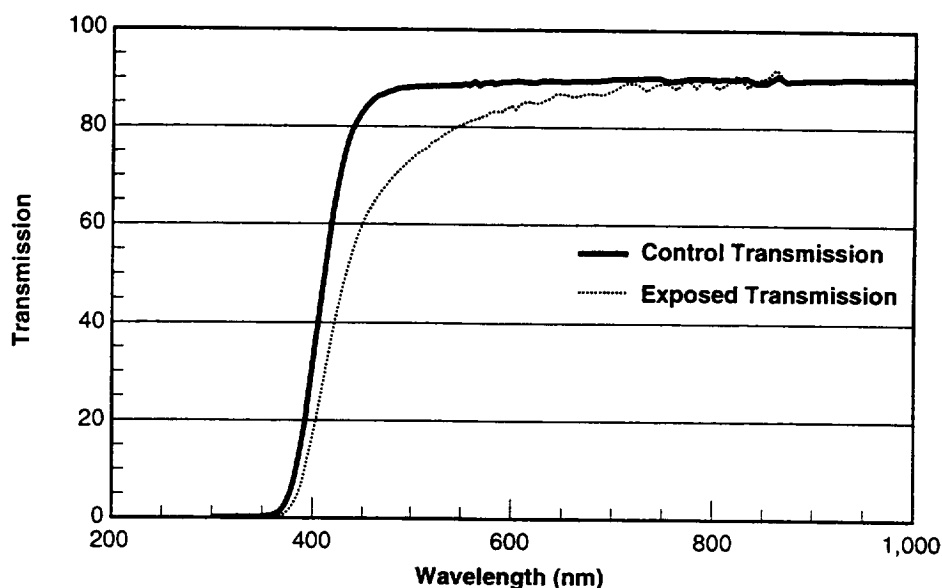


FIGURE 1. Transmission spectra of LaRC CP1 before and after exposure to 1300 ESH NUV in vacuum.

AEC Able identified several more candidate samples and requested a second NUV screening test. Pre-exposure transmission spectra were obtained and the sample exposure was initiated exactly as in the first screening test. Approximately 153 hours into this test, the NUV source failed and the test was prematurely terminated. The samples were analyzed and the test duration was recorded as a 420 equivalent Sun hours of NUV exposure. These samples and the test data are shown in Table 2.

Two materials, Teflon™ FEP (10 mils) and Teflon™ PFA (10 mils), were selected for an exposure to a combined effects environment.

This test was a combined charged particle exposure equivalent to 5 years in a typical GEO. This dose was determined by calculating the radiation dose as a function of depth in Teflon™ for a 5 year external exposure in a typical GEO (Coggi, 1996). This 5 year GEO dose-depth profile was compared to calculated dose-depth profiles in Teflon™ that were obtained using charged particle energies available in the CEE test system. The energy and fluence parameters of the CEE-available sources were analytically varied to produce a test dose-depth profile that best fit the 5 year GEO dose-depth profile obtained by Coggi (1996) (see Fig. 2).

TABLE 2. Polymers exposed to the second screening test, an exposure to 420 ESH NUV. Solar transmissivity values are shown for control and exposed polymers.

Material	Control Transmissivity (Tc) %	Exposed Transmissivity (Te) %	Transmission Degradation (Td) %
Teflon™ PFA (10 mils)	92.50	89.15	3.35
Teflon™ FEP (10 mils)	93.34	92.95	0.39
Tefzel 500 LZ (5 mils)	90.40	88.11	2.29
Aclar (5 mils)	92.86	92.40	0.46
UVR Teflon™ PFA (5 mils)	76.72	74.53	2.19

50 KeV electrons: 2.0 E15 e-/sq.cm 100 KeV protons: 1.05 E15 p+/sq.cm 400 KeV protons: 1.0 E13 p+/sq.cm
 220 KeV electrons: 1.35 E15 e-/sq.cm 200 KeV protons: 1.05 E14 p+/sq.cm 500 KeV protons: 5.0 E12 p+/sq.cm
 500 KeV electrons: 5.0 E14 e-/sq.cm 300 KeV protons: 2.5 E13 p+/sq.cm 700 KeV protons: 1.7 E12 p+/sq.cm
 NUV: 100 ESH

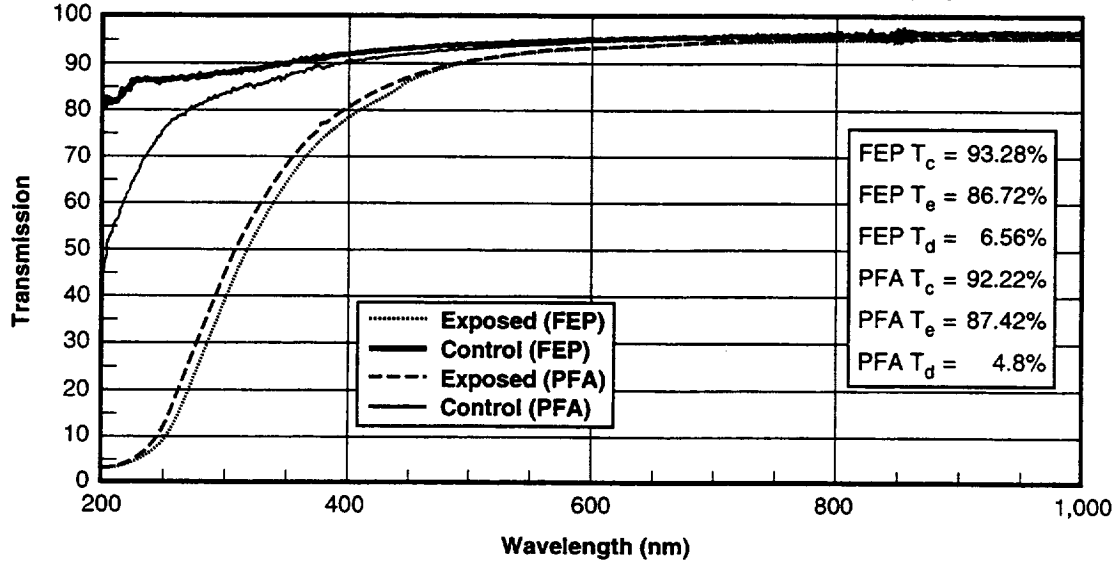


FIGURE 2. Transmission spectra of Teflon™ FEP and Teflon™ PFA before and after exposure to a 5 year equivalent GEO dose.

Transmission spectra of Teflon™ FEP and Teflon™ PFA were obtained prior to CEE exposure. The two samples were placed in the CEE test chamber and a base vacuum of 5×10^{-8} torr was established. The sample holder was maintained at 20 °C throughout the 5 year equivalent GEO charged particle exposure. Sample exposures varied from day to day but each source maintained a flux of 1 nA/cm² during irradiation. NUV exposure was included during each charged particle irradiation. The Teflon™ FEP and Teflon™ PFA samples were removed from the CEE system once the 5 year equivalent GEO charged particle dose was achieved and transmission spectra were obtained (see Fig. 2).

ANALYTICAL

The values for solar transmissivity, T_c and T_e as shown in Tables 1 and 2, were calculated using a technique modified from the procedure described by Wilkes (1969). The ASTM document E 490-73a lists the solar irradiance at AM0 over the wavelength range from 115 nm to 1×10^6 nm. The numerically integrated solar irradiance is quoted as 1353 W/m² over this wavelength range and is referred to as 1 solar constant at AM0. The modified technique applied in this effort utilized 102 specific wavelengths ranging from 300 nm to 1000 nm. This wavelength range was selected because it encompasses the operating range of several types of solar cells. Also, data obtained by reducing the transmission spectra in this wavelength range is applicable for solar thermal efforts. The individual irradiance values were determined using a linear interpolation which reduced the irradiance values to units of W/cm²*nm.

The solar transmittance, in W/cm², of the polymer was determined by multiplying the transmission of the polymer (T_λ) at a specific wavelength, and the solar irradiance (S_λ) at the same specific wavelength. This calculation yields the solar transmittance, in W/cm², of the polymer at a specific wavelength. This is expressed as:

$$(Ts)_\lambda = (T_\lambda) \times (S_\lambda) \quad (1)$$

The values of $(Ts)_\lambda$ are summed over the wavelength range from 300 to 1000 nm as:

$$\sum_{\lambda=300}^{1000} (Ts)_\lambda = Ts \quad (2)$$

It is important to note that this summation utilizes only 102 specific wavelengths out of the 700 wavelengths that are possible in this range.

The total solar irradiance (S) is defined, in this technique, as the sum of the 102 specific wavelengths over the range from 300 to 1000 nm. This is expressed as:

$$\sum_{\lambda=300}^{1000} S_\lambda = S \quad (3)$$

The value of S is constant and was determined to be 0.01413 W/cm².

The solar transmittance of the polymer was determined by the following:

$$T_s/S \times 100\% = T \quad (4)$$

Tables 1 and 2 list the values of T_c and T_e where $T_c \equiv$ solar transmittance of the polymer before exposure and $T_e \equiv$ solar transmittance of the polymer after exposure. These solar transmittance values can be used to analytically determine solar cell output provided the conversion efficiency of the solar cell is known. A GaAs solar cell was selected to demonstrate this procedure. The conversion efficiency of a standard GaAs solar cell is shown in Fig. 3 (Iles, 1990).

The power generated by the solar cell at each wavelength (P_λ) can be determined by

$$P_\lambda = \Theta_\lambda \times S_\lambda \quad (5)$$

where $\Theta_\lambda \equiv$ conversion efficiency at a specific wavelength λ and $S_\lambda \equiv$ solar irradiance at AM0 at wavelength λ . Summing the values of P_λ over the wavelength range from 500 nm to 900 nm for GaAs yields a total power generated of 0.0254 W/cm².

The power generated by a solar cell with a transparent polymer in the optical path can be determined by the following,

$$P_\lambda = \Theta_\lambda \times (T_s)_\lambda \quad (6)$$

The total power generated by the solar cell with a transparent polymer in the optical path illuminated by 1 solar constant at AM0 is given by

$$\sum_{\lambda=500}^{900} P_\lambda = P \quad (7)$$

Solar cell power values, with the effect of a transparent polymer in the optical path, were calculated for several polymers shown in Table 1. These values of solar cell power are shown in Table 3.

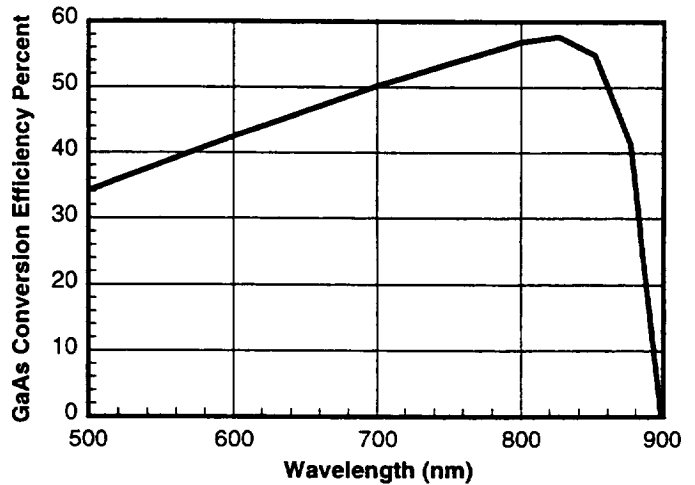


FIGURE 3. Conversion efficiency versus source wavelength for GaAs solar cells with an input power of 1 W/cm².

TABLE 3. GaAs solar cell power calculated with transparent polymer material in the optical path.

Solar Cell Power Calculated With Material In Optical Path			
Material	Material Pre-Exposure W/cm ²	Material Post-Exposure W/cm ²	Exposure Environment
Lexan	0.0226	0.02	1300 ESH NUV
LaRC CP1	0.0227	0.0215	1300 ESH NUV
Tefzel 500 LZ	0.0235	0.0217	1300 ESH NUV
Acrylic	0.0246	0.0221	1300 ESH NUV
UVR T2 Tefzel	0.023	0.0221	1300 ESH NUV
Teflon™ PFA	0.0242	0.0217	1300 ESH NUV
Triton COR	0.0225	0.0201	1300 ESH NUV
Teflon™ FEP	0.024	0.0236	5 year GEO

CONCLUSIONS

Transparent polymer usage as a solar concentrating lens is dependent on the ability of the polymer to maintain optical integrity while in the space environment. These flexible polymer lenses offer a number of distinct advantages from both the power system cost and manufacturability perspectives. Even with these advantages, these materials must demonstrate long-term optical performance in the relevant space environment.

A large number of commercially available transparent polymers have been investigated to determine the effect of various simulated space environmental exposures on the polymer transmission. A method was presented that calculates solar transmissivity over the wavelength range from 300 to 1000 nm. This method allows the polymers to be ranked according to the tolerance of the space environmental exposure. A technique was also described that demonstrates the effect of transmission degradation on the power output of a standard GaAs solar cell. This technique can be used first to choose an optimum polymer/cell pair and second, to determine the solar cell surface area needed to maintain spacecraft power requirements throughout the mission lifetimes.

The results obtained in this study provide a small, but significant, contribution to the database necessary to further the development and implementation of transparent polymers for space. Continued material development and quantitative testing is expected as the applications for these materials continue to expand.

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